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MATERIALS RESEARCH HIGHLIGHT

Frontiers in thermoacoustic refrigeration and mixture separation

S. Backhaus[1], D. Geller[2], B. Ward[2], and G. Swift[1]

Thermoacoustics is a rapidly developing field of energy conversion, which harnesses the oscillations of temperature, heat flux, pressure, and motion in intense sound waves.

Stirling's "hot-air engine" of the early 19th century was one of the first heat engines to use oscillating thermodynamics in a gas in a sealed system. Since then, many related engines and refrigerators have been developed. The efficient, mature members of this family of engines and refrigerators are used in several niche markets, ranging from small cryocoolers with cooling powers below 10 watts to large engines with powers near 100 horsepower. Applied developments in which Los Alamos has been or is involved include a combustion-powered thermoacoustic natural gas liquefier, radioisotope and reactor-driven thermoacoustic engines for generating electrical power on spacecraft, and heat-driven thermoacoustic engines and engine–refrigerator systems for electric-power generation and air conditioning for military and civilian uses.

Much of the evolution of this entire family of oscillating-gas thermodynamic technologies has been driven by the desire for simplicity, reliability, and low fabrication costs without seriously compromising the Stirling cycle's high energy efficiency. The Los Alamos "thermoacoustics" approach has contributed many of these simplifications and has emerged as a unifying perspective for the entire family of technologies. Our approach has been successful because it is strongly grounded in a combination of fundamental experiments, theoretical analysis of microscopic processes, and proof-of-principle experiments. In addition to our mostly proprietary applied work with U.S. companies, we continue to explore fundamental questions in thermoacoustics, as described below.

Refrigeration research

Pulse-tube refrigerators reliably provide cryogenic refrigeration powered by acoustic energy. A pulse-tube refrigerator, shown in Figure 1, is a sealed unit made of several heat-transfer and acoustic components and filled with a gas—typically high-pressure helium. Refrigeration is produced because gas that oscillates through the cold heat exchanger is depressurized adiabatically on the pulse-tube side, but is pressurized isothermally on the regenerator side. This broken symmetry causes the gas to cool the cold heat exchanger as it passes through it from pulse tube to regenerator. The other components in the refrigerator create the oscillating pressure and motion with the correct amplitudes and time phases, and isolate the refrigeration from waste heat rejection at the two ambient heat exchangers.

We are currently pursuing fundamental research on two aspects of pulse-tube refrigeration.

First, we are studying the basic physics of convection in the pulse tube itself. The pulse tube is an open tube in which thermally stratified, purely oscillating flow is desired. Gravity helps stabilize this thermal stratification when the tube is oriented with its cold end down, but gravity-driven convection can ruin the thermal stratification and harm the refrigeration power and efficiency when the pulse tube is oriented sideways (as in Figure 1). Under some circumstances, however, the oscillations themselves stabilize the thermal stratification in the sideways-oriented pulse tube.

Second, we are studying a new way of staging two pulse-tube refrigerators in series. The orifice-inertance-compliance network of the standard pulse-tube refrigerator shown in Figure 1 dissipates acoustic power by design because power must flow through the cold heat exchanger to cause the desired refrigeration. We are developing a new way of using that acoustic power

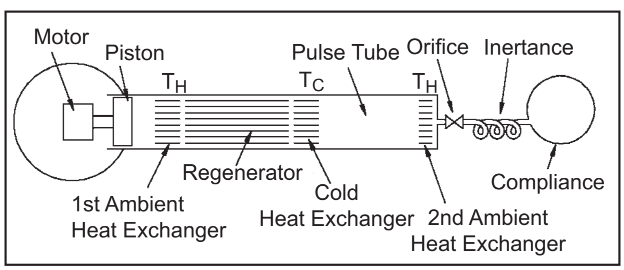

Figure 1. A pulse-tube refrigerator with acoustic input provided by an electric motor at the left end and phase controlled by an acoustic impedance termination at the right end. The gas velocity in between is generally from left to right while the pressure is high and the opposite direction while the pressure is low.

[1]Materials Physics and Applications Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[2]Applied Engineering Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

and the inertial characteristics of the gas motion in the pulse tube to drive a second, smaller pulse-tube refrigerator while keeping optimal time phasing between pressure and motion oscillations in the first, larger pulse-tube refrigerator.

Mixture-separation research

In thermoacoustic mixture separation, a sound wave in a gas mixture near a solid boundary causes one component of the mixture to scoot along the boundary in one direction, while the other component scoots in the other direction. Figure 2 illustrates the process. The high and low extremes of pressure p in the sound wave, in steps (a) and (c), cause high and low extremes of temperature T, which in turn cause oscillating thermal diffusion of the two components of the mixture in the y direction, so they take turns partially hiding in the viscous boundary layer near the solid. Thus, during the gas motion u along the surface, in steps (b) and (d), light-enriched gas moves one way, while heavy-enriched gas moves the other way. As this process repeats for every oscillation of the sound wave, and everywhere along a long tube, the separation proceeds—bucket-brigade fashion.

High-purity thermoacoustic mixture separation requires tubing many wavelengths long. Maintaining a sound wave in such a long separation tube is challenging because the separation process relies on the gas boundary layers at the tube wall, which dissipate acoustic power. The reliability and low cost of a thermoacoustic mixture separator might be seriously compromised if hundreds of sound sources had to be periodically connected to a separation tube to make up for this dissipation.

We are studying one way to avoid such a large number of sound sources, illustrated in Figure 3. The separation tube will be coiled so each turn of the coil is one wavelength. The coil will be packaged in a rigid toroidal shell full of liquid, and a few hydraulic drivers will make a pressure wave in the liquid, which will travel around the torus at a speed matched to the speed of sound in the gas in the separation tube. The tube's cross section will be slightly elliptical so that its local cross-sectional area will respond to the liquid pressure, peristaltically driving the wave in the gas within. Such equipment might be used for small-scale isotope enrichment, e.g., for stable isotopes used in nuclear magnetic resonance (NMR) medical imaging.

We have also begun to extend our studies of thermoacoustic mixture separation to three- and four-component, chemically reacting mixtures. At high enough temperatures the sound wave's oscillating pressure and temperature shifts the equilibrium of reactions back and forth at the acoustic frequency, leading to a new thermoacoustic separation mechanism that does not rely on the thermal diffusion process shown in Figure 2.

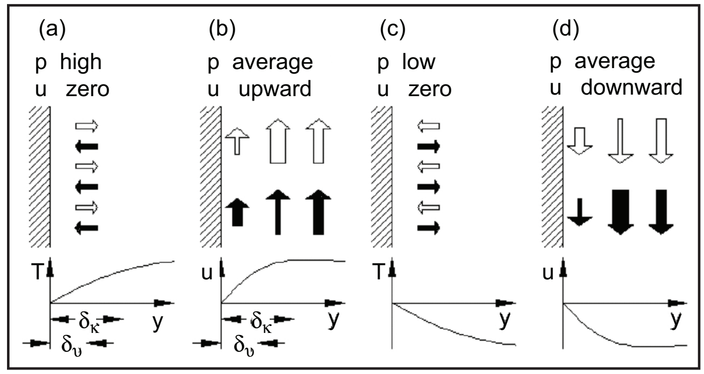

Figure 2. Filled arrows represent the motion of heavy molecules in a gas mixture; open arrows represent light molecules. The length of the arrows represents motion and the width represents local concentration. A four-step process in and near the thermal and viscous boundary layers, δ_κ and δ_ν respectively, causes a net upward motion of light molecules and downward motion of heavy molecules. The solid wall at y=0 is crucial for all four steps.

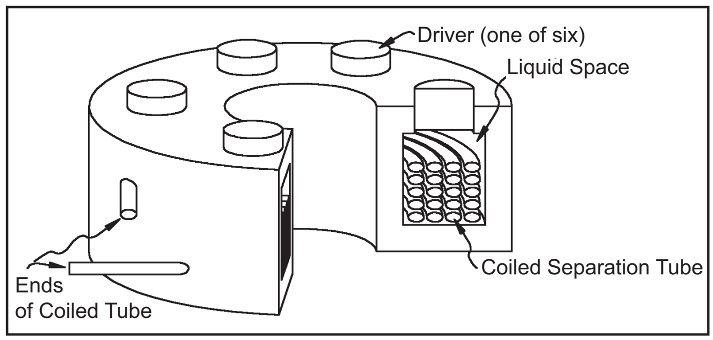

Figure 3. A coiled, peristaltically driven thermoacoustic tube can accomplish high-purity thermoacoustic mixture separations in a long tube with a small number of drivers and no leak-prone joints in the tube.

Biographies

Scott Backhaus (PhD physics, University of California, Berkeley) works on thermoacoustics in the Condensed Matter and Thermal Physics Group. At Los Alamos, he has won a Reines Fellowship, an R&D 100 Award, the Postdoctoral Publication Prize in Experimental Science, and the World Oil New Horizons Award.

Drew A. Geller (PhD physics, Cornell University) came to Los Alamos as a Director's Postdoctoral Fellow to work on thermoacoustics, focusing on the phenomenon of mixture separation. He is a technical staff member in the Tritium Science and Engineering Group.

Bill Ward (PhD acoustics, Pennslyvania State University) is the team leader for new developments in the Nondestructive Testing and Evaluation Group and is a winner of the Department of Defense's Award of Excellence for radiographic testing.

Greg Swift (PhD physics, University of California, Berkeley) is a member of the Condensed Matter and Thermal Physics Group and a Fellow of the American Physical Society, of the Acoustical Society of America, and of the Laboratory. The main focus of his research has been the invention, analysis, and development of novel energy-conversion technologies, especially thermoacoustics.